Mechanisms governing avulsions in transient landscapes: Analysis of the May 2006 Suncook River avulsion in Epsom, New Hampshire

by

Mariela C. Perignon

Submitted to the Department of Earth, Atmospheric and Planetary Sciences in Partial Fulfillment of the Requirements for the Degree of Bachelor of Science in Earth, Atmospheric and Planetary Sciences at the Massachusetts Institute of Technology

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ABSTRACT

Avulsions, or rapid changes in the location of a river, usually occur in environments such as deltas, floodplains, and alluvial fans where net-deposition can raise the bed of the river above its floodplain. Avulsions are less frequent in transient landscapes, such as New England, where topography and hydrography are still responding to recent glaciation. One of these rare avulsions occurred during a 100-year flood on the Suncook River, Epsom, NH, between May 14 and 15, 2006.

We studied the Suncook River event to develop a model for the drivers of avulsions in transient landscapes. We suggest that a strong substrate in the parent channel, such as bedrock or immobile boulders, can facilitate an avulsion by preventing incision and driving water overbank. Easily erodible substrates in the path of the new channel can also contribute to avulsions by allowing a knickpoint to migrate quickly upstream and create a channel with a more favorable slope during a single flood. Based on Slingerland and Smith's (2004) model, we also propose that a low water-surface slope in the parent channel could be a direct driver for avulsions. In the Suncook River, this low water-surface slope was created in the backwater of a small mill dam in the parent channel.

A 200-year flood that occurred in the Suncook River in 1936 did not create an avulsion. We suggest that ice floats could have damaged the dam and increased the water-surface slope of the parent channel, making an avulsion less favorable and reducing the depth of water flowing overbank. The topography in the path of the 2006 avulsion, which was lowered by activity in a sand pit starting in the 1960s, probably prevented water from finding a new path. We believe that these anthropogenic modifications directly contributed to the occurrence of the May 2006 avulsion in the Suncook River. These conditions are common throughout New England, and could increase the risk of avulsions in the region.

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Chapter 1

Introduction

The positions of channels in deltas, alluvial fans, and floodplains change frequently on geological time scales. Abrupt changes, referred to as avulsions, create new channels that capture some or all of the flow of a previously established river. The relocation of rivers during avulsions contributes to the distribution of sediment on floodplains, and thus directly affects the patterns of drainages and the architecture of fluvial sedimentary deposits on the surface.

Avulsions are also common in modern drainage systems, and often cause havoc in our attempts to control the paths of rivers. The Mississippi River delta, for example, has changed position at least seven times in the past 5000 years (Kolb and Van Lopik, 1966) (Figure 1). Fisk (1952) also recognized the Atchafalaya-Mississippi bifurcation as an incipient avulsion. If this switch were allowed to occur, the Mississippi would run a new course farther west than it is now, leaving the port of New Orleans dry and severely disrupting commercial cargo traffic in the United States. The Old River Control Structure presently keeps water out of the Atchafalaya River in an attempt to prevent this switch. This path, however, is gravitationally more favorable for the river to take.

Most avulsions occur at smaller scales. One of these small avulsions occurred on the Suncook River in the town of Epsom, New Hampshire, in May 2006. Heavy rains between May 11 and May 15 dramatically increased the discharges of many New England rivers. Between May 14 and 15, the Suncook River, a tributary to the Merrimack River, left its path and carved a new channel outside of its established floodplain. There

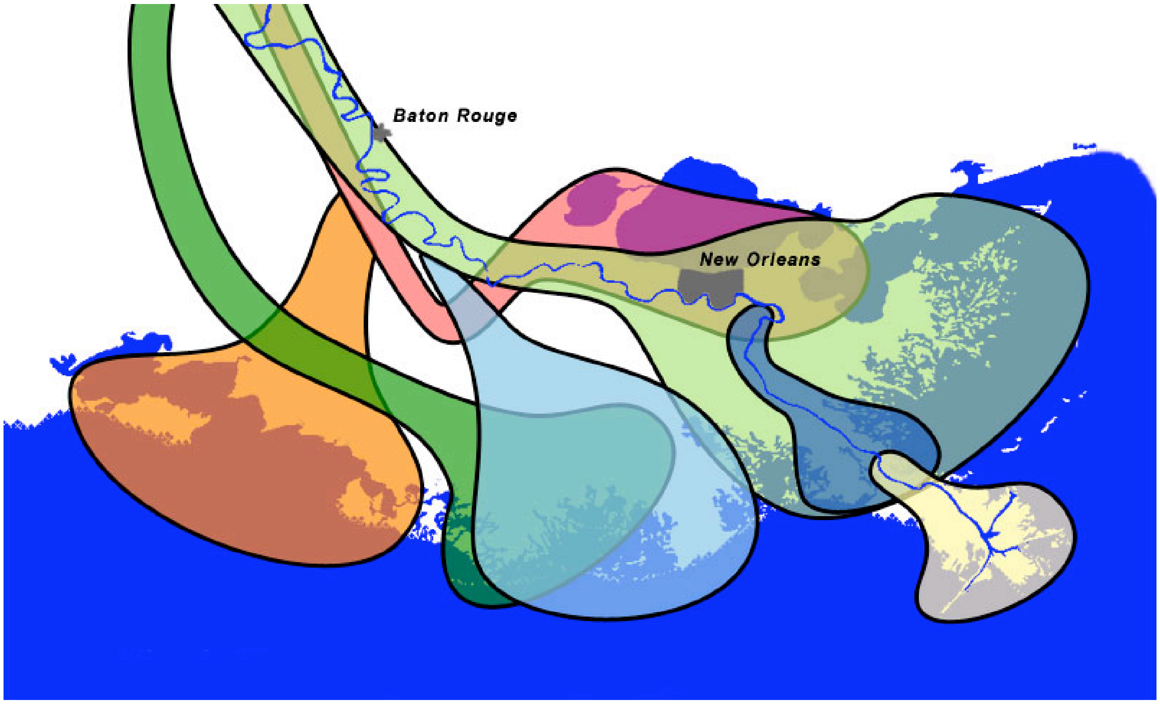

Figure 1: Deltaic lobes of the Mississippi River. Balize lobe (550 years ago to present) is marked with a black arrow (Public domain image, modified from Kolb and Van Lopik, 1966).

was no loss of life, but the flood deposited thick layers of sediment on downstream banks, isolated or eroded away pastures and agricultural land, and increased the flood risk for hundreds of homes (Orff, 2006).

Most of our understanding of avulsions comes from studies of these events in alluvial fans, deltas, and floodplains, as well as in the stratigraphic record that these environments create. Rivers in these environments have been steadily aggrading for thousands of years. Avulsions occur more frequently and at larger scales in these landscapes because the migration of channels is not restricted by topography or vegetation, but are instead free to take any path. The Suncook River event is one of the few avulsions that have been recorded in New England. Several more have been found using aerial photographs but have not been studied.

The geological history of New England is also different from that of the environments where avulsions commonly occur. During the Wisconsinan glaciation, which ended 12000 years ago, thick glaciers covered northeastern United States. When the glaciers retreated, they left behind boulders, gravels and sands that modified the topography and erosional and depositional patterns in the landscape. The continuing response of the regional hydrology to this recent period of glaciation makes New England a transient landscape.

Currently, there are no models that have been created to explain avulsions in transient landscapes. In this work we present the first stages of the development of a model for avulsions in these environments. We looked at previously established models for the occurrence of avulsions in net-depositional landscapes in order to develop our own theories.

Models for avulsions in aggrading rivers are based on the formation of topography by spatially varied deposition of sediment on the floodplain. Deposition rates are highest in channels and along their immediate banks (Pizzuto, 1987), while the thickness and mean grain size of deposits in floodplain decrease with distance from an active channel (e.g. Marriott, 1992; Guccione, 1993; Middelkoop and Asselman, 1998). This variation in aggradation rates gradually raises channel above the surrounding floodplain while still retaining its cross-sectional shape and transport capacity (Mohrig et al., 2000, Makaske, 2001; Makaske et al., 2002; Törnqvist and Bridge, 2002).

Two models have been proposed to explain the mechanics that drive avulsions in aggradational landscapes. Some researchers suggest that avulsions occur when the ratio of the cross-sectional slope of a channel levee and the slope of the long profile of the channel is large (e.g., Allen, 1965; Hooke and Rohrer, 1979; Wells and Dorr, 1987; Brizga and Finlayson, 1990; Mackey and Bridge, 1995; Slingerland and Smith, 1998, Jones and Schumm, 1999, Törnqvist and Bridge, 2002). Others propose that the driver for avulsions is the existence of relief between the elevation of the water surface at bankfull discharge, estimated by the height of channel levees above the bed, and the lowest point in the surrounding floodplain. Rivers are thought to avulse as this ratio approaches a value of 1 and the bed of the channel reaches the elevation of the floodplain (e.g., Brizga and Finlayson, 1990; Bryant et al., 1995; Heller and Paola, 1996; Mohrig et al., 2000).

Slingerland and Smith (2004) propose a model for avulsions based on bifurcation stability. They suggest that the ratio between the water surface slopes of the new channel and the parent channel determines the type of avulsion that occurs. We chose to use their model to study the Suncook River avulsion because, while their theory is similar to the levee slope model, it can be applied to rivers without well-defined levee systems.

The purpose of our research is to understand what controls avulsions in transient landscapes. We would like to know if the mechanisms that are thought to control avulsions in net-depositional environments are also be responsible for the avulsion that occurred in the Suncook River. We would also like to answer basic questions about the magnitude and importance of the May 2006 flood in the hydrologic history of the Suncook River in order to determine possible factors that facilitated this event. Answering these questions will allow us to take a first step towards developing a model to understand avulsions in transient landscapes.

Chapter 2

Events That Led to the Suncook River Avulsion – Geographic and Geologic Setting

The Merrimack River forms at the confluence of the Pimagewasset and Winnipesaukee rivers near the town of Franklin, New Hampshire. The river then flows south for 125 km until it reaches the NH-MA border, where it turns east and flows 129 km to its mouth into the Atlantic Ocean at Newburyport, MA. The Merrimack River and its tributaries define the fourth largest watershed in New England, with a total drainage area of 13,000 km^2 (CDM, 2003).

The Suncook River in southeastern New Hampshire is a minor tributary to the Merrimack River. It begins at Crystal Lake, east of Gilmanton and north of Barnstead, NH. Crystal Lake forms from drainages originating in the Belknap Mountains. The Suncook flows southwest until it reaches the Merrimack River near the town of Suncook Village. Along its course the Suncook River receives only one major tributary, the Little Suncook River. The total length of the Suncook River is 63 km from its origin to its confluence with the Merrimack, with a total drainage area of 663 km^2 (CDM, 2003).

2.1. Events Leading to the May 2006 Floods

In early May 2006 a low-pressure atmospheric system developed over Scandinavia and migrated west while staying at high latitudes (Climate Prediction Center, 2006). These low-pressure systems are often referred to as "blocks" because they slow down the migration of atmospheric systems and create repeating climatic conditions in a geographic area. Between May 12 and 15 this low-pressure system was stationed over eastern Canada. Southeast winds carrying moisture from the Atlantic Ocean formed a circulating storm system that brought heavy rains throughout New England (Climate Prediction Center, 2006). 30 to 38 cm of rain fell throughout New Hampshire in that period (Figure 2), with local measurements of up to 43 cm measured near Epson, NH (Orff, 2006). The low-pressure system continued moving west, reaching western North America on May 17 and allowing the storms over New England to dissipate (Climate Prediction Center, 2006). Many rivers in Massachusetts, New Hampshire, Vermont, and Maine flooded as a result of the heavy precipitation.

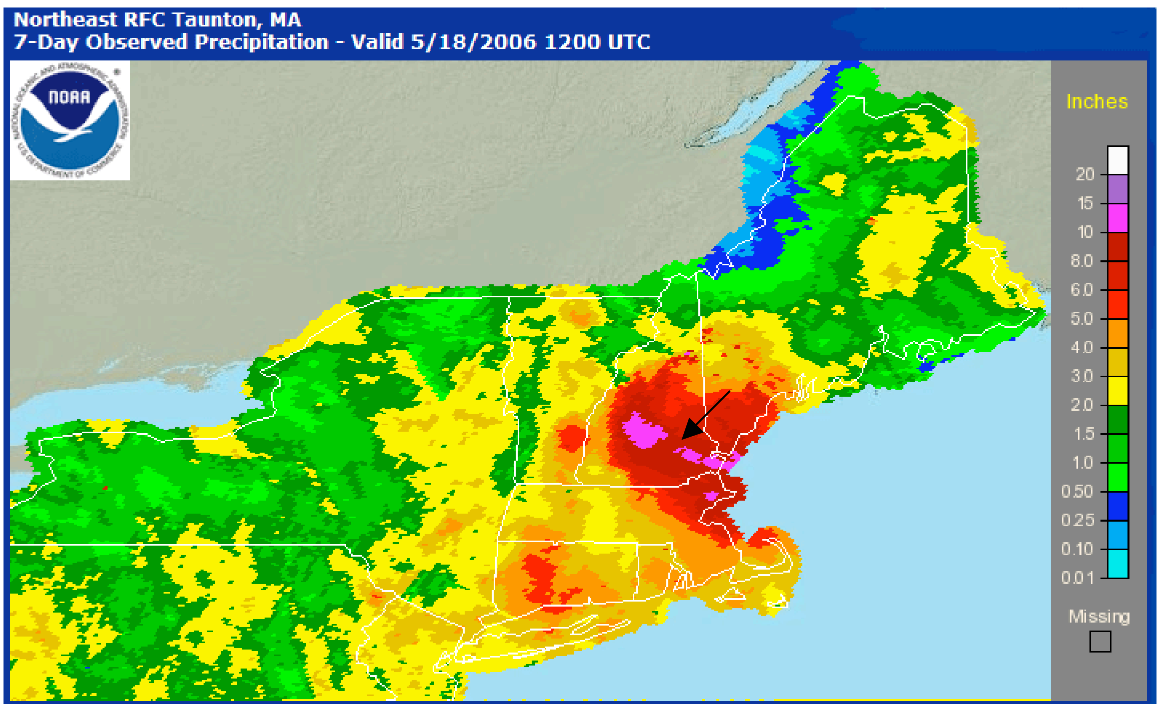

Figure 2: Total rainfall for New England between May 11 and 18, 2006. Black arrow marks location of Suncook River (Modified from Climate Prediction Center, 2006).

2.2. Geometry of the Avulsion Site

The site of the 2006 avulsion is located in the town of Epsom, NH, 15 km upstream of the confluence of the Suncook with the Merrimack River. The field site can be accessed by traveling along the Suncook Valley Highway (New Hampshire road 28) and turning onto Old Mill Road to reach Huckins Mill Dam and the now abandoned main channel. The avulsion site is 700 meters northeast (upstream) (Figure 3).

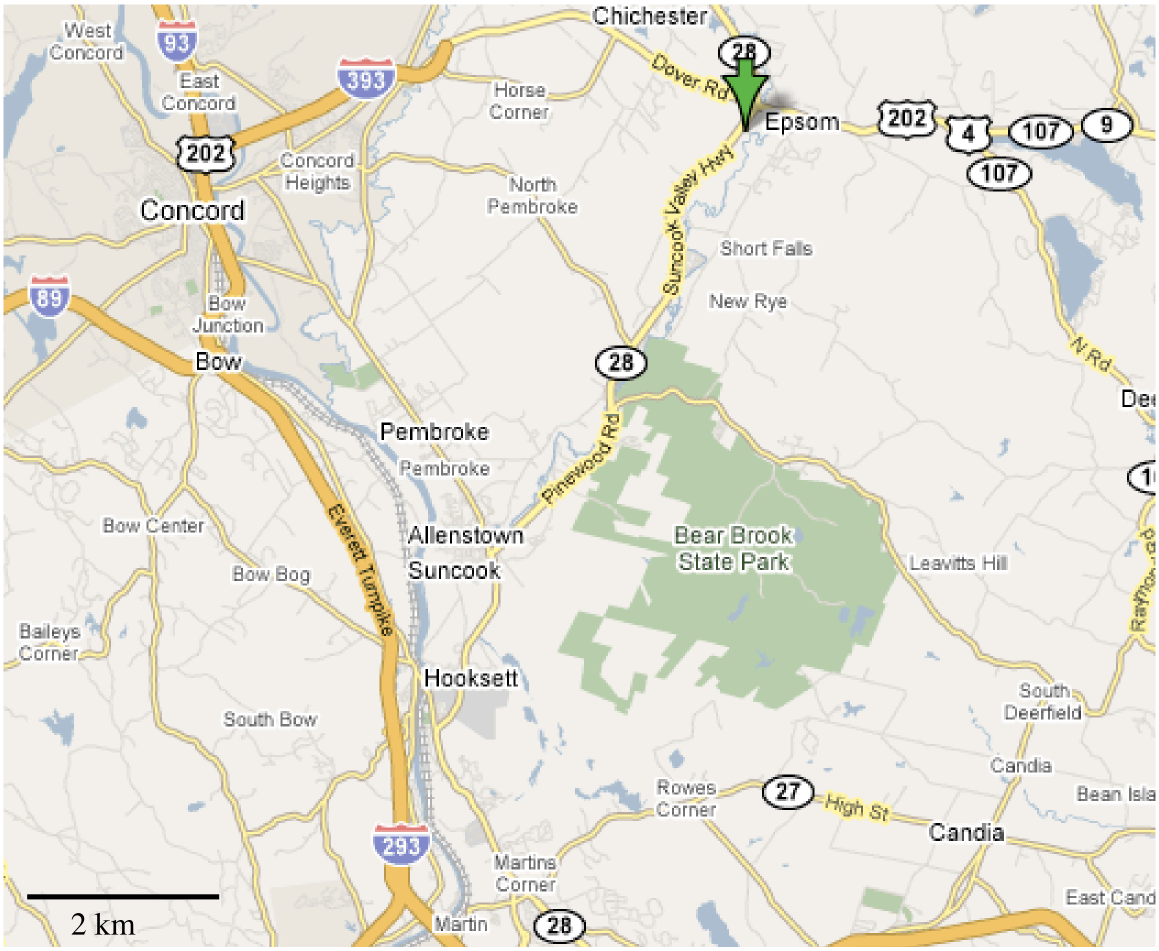

Figure 3: Map of major roads around the Suncook River avulsion site, marked by the green arrow (Google Maps).

The Suncook River formerly split into two branches: a primary, western channel and a secondary, eastern channel (Figure 4). The 4 m high Huckins Mill Dam, also known as Old Mill Dam, controls flow in the primary channel. The bifurcation between the primary and secondary channels is located 30 m upstream of Huckins Mill Dam. A smaller retention dam, 1.5 m high, blocks the secondary channel at this location.

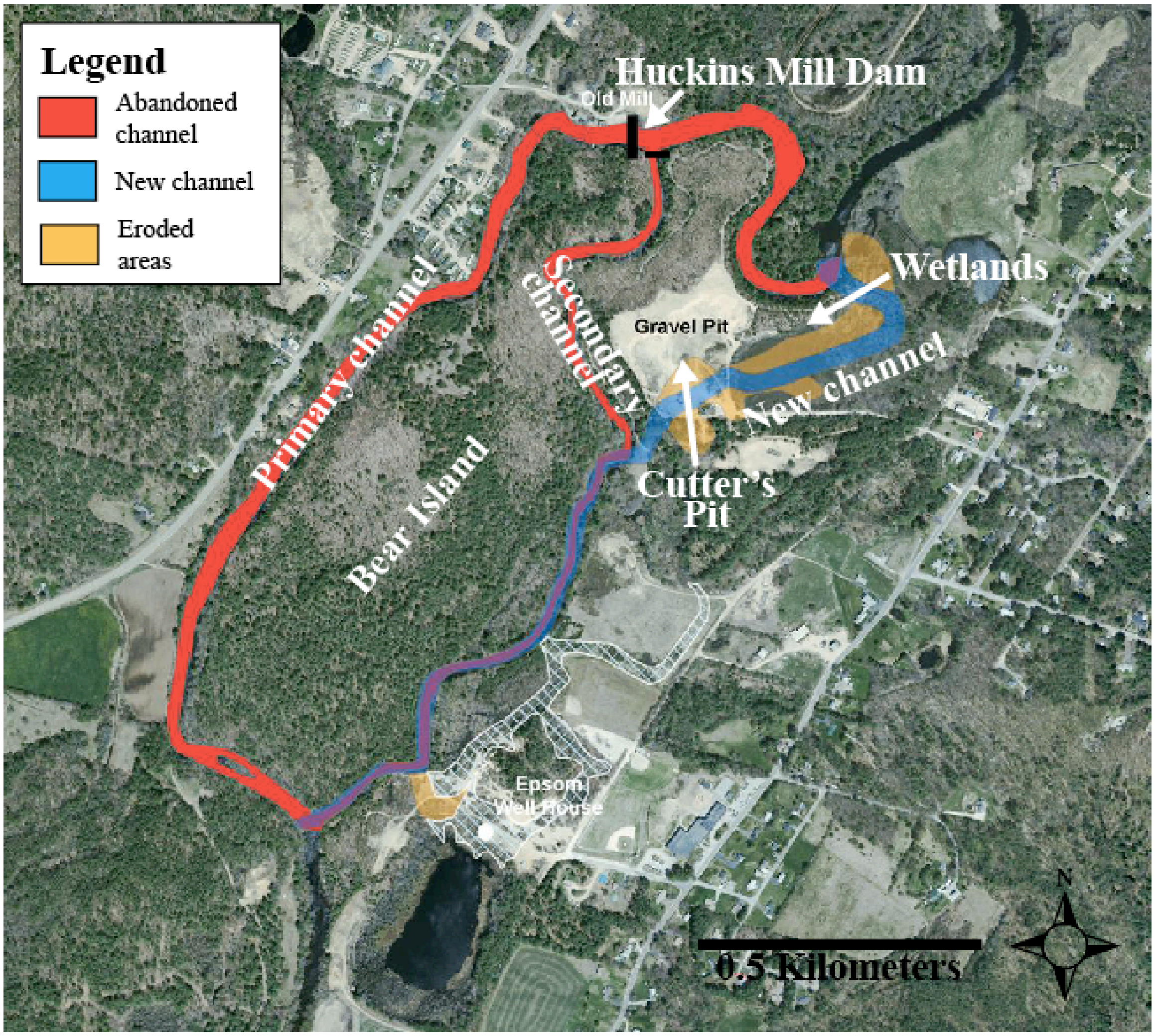

Figure 4: Aerial photograph of the Suncook River avulsion site showing important features. The pre-avulsion channel is pictured in red, and the new channel in blue. Note that the downstream section of the new path occupies a portion of the secondary channel (Modified from New Hampshire Geological Survey).

These dams were built in the late 1800s as part of a sawmill and rebuilt in 1937 after a series of large floods. Before the 2006 avulsion, water was impounded for 2 km upstream of these dams, with a total impound area of 0.11 km^2 (NHDES Dam Bureau). The high-relief area between the primary and secondary channels is known as Bear Island, and is the site of a privately owned campground.

Upstream of the bifurcation between the primary and secondary channels the Suncook River takes a sharp turn to the west and then another back to the south.

Wetlands grew in this zone at bankfull elevation. The higher area between this bend and the secondary channel was mined for sand. Cutter's Pit, as the sand quarry is known, had dug at least 6 meters of material from this area between its opening in the 1960s (Connaboy, 2006b) and May 2006, leaving a large depression with a base elevation close to bankfull levels. Although most of the pre-avulsion geometry of Cutter's pit has been destroyed, remnant topography, aerial photographs, and anecdotal evidence suggests that quarrying operations left a ridge around the pit. This ridge was around 10 m high on the downstream end but very low close to the river. Roads for heavy machinery lead to and from the quarry, with one of these roads encircling the pit. Accounts of local residents suggest that vehicles and heavy machinery traveled off-road over the downstream ridge to reach this road, lowering the height of the ridge from 10 m to 1.5 m above the floor of the pit (Rick Griggs, personal communication).

2.3. The May 2006 avulsion

As the flow depth of the river increased during the May 2006 flood, water flowed overbank and pooled on the floodplain around the channel. Water also made its way over the wetlands and into Cutter's Pit. The pit gradually filled with water as the discharge of the Suncook continued to increase. Stagnation of the flow in the pit and the wetlands allowed sediment in the water column to settle.

Wittkop et al. (2007) present evidence for high-water marks in and around Cutter's Pit that show that water pooled to a depth of 1.5 m. At this depth, water could flow over the gap that vehicles eroded on the back wall. The removal of the ridge by the flow occurred rapidly, creating a steep drop from the base of the quarry onto the downstream floodplain. Water then flowed into the secondary channel of the Suncook. The step or knickpoint migrated gradually upstream until it reconnected with the main channel of the Suncook River at what is now the avulsion site. The migration of the knickpoint was not uniform and gradual, but was seen by local residents as occurring by episodic collapse. As it carved the new channel, the water also eroded terraces onto the sand pit and deposited thick layers of the removed material on the downstream floodplain (Figure 5).

Figure 5: Cutter's Pit, looking downstream, on May 16, 2006. Notice the high ridge surrounding the quarry. Water broke through a site of lower elevation on this ridge created by vehicles passing to and from the quarry. Floodwaters also cut a terrace onto the quarry floor (right).

When the knickpoint reached the avulsion site, flow was diverted from the principal channel of the Suncook onto the newly carved channel. Eyewitnesses reported water flowing upstream from Huckins Mill Dam as the impounded water drained (Orff, 2006). Water pooled in the principal channel as well as the surrounding floodplains and the newly formed channel while flood levels remained high (Figure 6). As the discharge of the Suncook River returned to normal, the principal channel dried up and all the flow was routed to the new channel.

Figure 6: Aerial view of the avulsion site of the Suncook River on May 17, 2006. River flows through top to bottom. Main channel (left) is draining onto new channel (right) (Steward Yeaton).

The new channel of the Suncook River formed outside of both the 100-year and 500-year flood zones defined by the FEMA flood insurance rate maps of 1978 (Figure 7).

It transverses the wetlands and the sand pit and connects the main Suncook River to the secondary channel. The primary channel and the upstream reaches of the secondary channel, as well as both dams, are now abandoned and carry no flow.

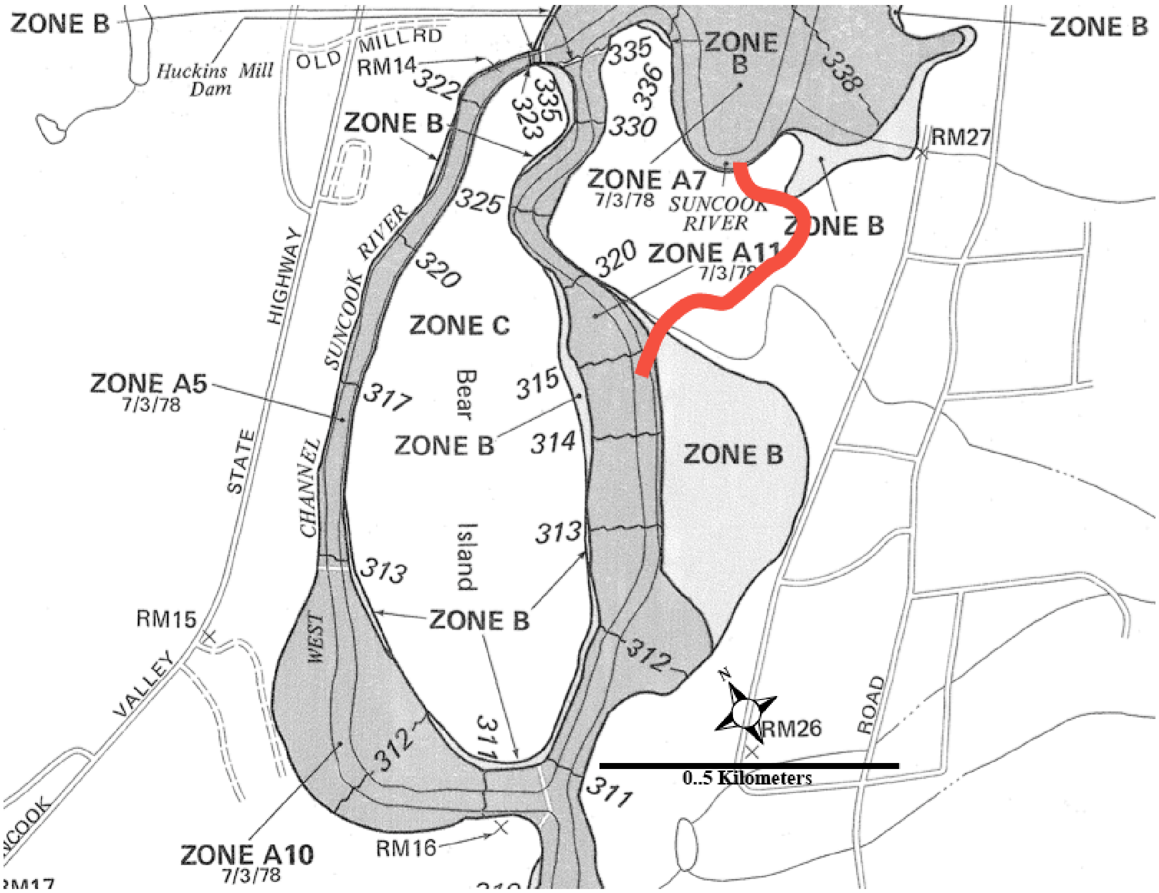

Figure 7: Approximate location of the newly carved section of the Suncook River on the FEMA flood insurance rate map of 1978. Dark gray zone (Zone A) corresponds to area flooded by 100-year floods. Light gray zone (Zone B) corresponds to 500-year flooding areas. The avulsion created a new channel outside of these two zones. FEMA flood insurance rate maps will have to be redrawn to take into account the new geometry of the river (Modified from FEMA, 1978).

2.4. Geologic Setting

The geology of New Hampshire exposes the core of an ancient mountain range. Bedrock composed of strongly deformed and metamorphosed Paleozoic sedimentary and metamorphic rocks that have been intruded by several generations of plutonism (Billings, 1956). These rocks form belts that run roughly northeast-southwest, perpendicular to the direction of collision during the middle to late Devonian Acadian Orogeny that formed the Appalachian Mountains (Marvinney and Thompson, 2000). The bedrock of southeastern New Hampshire has been dated as approximately Ordovician to Silurian in age and is composed of several metavolcanic and metasedimentary units of varied lithologies. The bedrock of our field site is the lower member of the Silurian Rangeley Formation, a stratified, high-grade metapelite. The strike-slip Pinnacle fault forms the eastern margin of the Suncook River valley. Between Epsom, NH, and the confluence with the Merrimack River, the Suncook runs along the strike of this fault (Lyons et al., 1997).

Glaciation strongly shaped the landscape of New Hampshire. The Late Wisconsinan, the most recent glacial period, started around 25 ka. During this time, glaciers covered eastern North America as far south as Rhode Island. The direction of the movement of these glaciers determined the northwest-southeast trend of glacial forms. Ice started retreating between 17 ka and 15 ka, and cleared New England of ice by 12 ka (Flanagan et al., 1999).

The Suncook valley was the site of an arm of glacial lake Hooksett. The water level of the lake was controlled by a spillway in the Merrimack valley, south of the modern confluence of the Merrimack and Suncook rivers (Flanagan et al., 1999). Outwash from retreating glaciers deposited the thick sequence of rhythmically bedded clays and sands that the new Suncook River channel cuts through and that Cutter's Pit was mining prior to the avulsion.

Bedrock is exposed in our field area in the upstream section of the secondary channel as well as downstream of Huckins Mill Dam. It has also been mapped to be within 3 m of the surface for the 50 m of the primary channel upstream of the Huckins Mill Dam (Goldsmith, 1998). Bedrock exposed in the channels is eroded into rounded shapes with well-developed potholes.

Several reaches of boulders that have not been previously mapped are exposed in the primary and secondary channels, as well as upstream of the avulsion site. These boulders are angular and formed of coarse-grained granite and the local bedrock lithology. Their exposed surfaces are covered in a black patina that formed from extended exposure to impounded water, showing that they have not moved in recent floods. At a few locations in the new channel they appear to be part of a glacial clay layer, suggesting that they could be dropstones. The mixed lithologies also suggest that they are not from a nearby source.

Chapter 3

Reconstructing the Flooding History for the Suncook River

Floods affect a larger population in the state of New Hampshire than any other natural hazard (New Hampshire Department of Safety Natural Hazard Mitigation Plan). Table 1 shows all major floods recorded in New Hampshire that have affected the Merrimack Basin. In order to understand the processes that lead to the avulsion of the Suncook River, we must look the magnitude of the specific flooding event that caused the avulsion to understand its role in the historical record. This can help us determine how the

Table 1: Major floods in the history of New Hampshire that have affected the Merrimack Basin (modified from New Hampshire Department of Safety Natural Hazard Mitigation Plan).

Date	Flooding basins
December 1740	Merrimack River
October 23, 1785	Cocheco, Baker, Pemigewasset, Contoocook and Merrimack Rivers
March 24-30, 1826	Pemigewasset, Merrimack, Contoocook, Blackwater and Ashuelot Rivers
April 19-22, 1862	Contoocook, Merrimack, Piscataquog, and Connecticut Rivers
October 3-5, 1869	Androscoggin, Pemigewasset, Baker, Contoocook, Merrimack, Piscataquog, Soughegan,Ammonoosuc, Mascoma, and Connecticut Rivers
November 3-4, 1927	Pemigewasset, Baker, Merrimack, Ammonoosuc and Connecticut Rivers
March 11-21, 1936	Statewide
September 21, 1938	Statewide
June, 1942	Merrimack River
June, 1944	Merrimack River
April, 1960	Merrimack and Piscataquog Rivers
April, 1969	Merrimack River Basin
March 14, 1977	South-central and Coastal New Hampshire
July – August 10, 1986	Statewide
August 7-11, 1990	Statewide
August 19, 1991	Statewide
June – July 1998	Central and Southern New Hampshire
May, 2006	Statewide

changing geometry of a river and its floodplain, as well as the anthropogenic changes that have taken place in the last century, can affect the occurrence of an avulsion.

3.1. Finding a Proxy for the Discharge of the Suncook River

The only record of water discharges for the Suncook River comes from a USGS gage located near Chichester, NH, that was active between 1918 and 1970. In order to reconstruct a complete historical record that included the May 2006 flood we looked at nearby rivers to choose a proxy for the discharge of the Suncook. We chose the Soucook River and the Piscataquog River as potential proxies for the Suncook (Figure 8). The watershed of the Soucook River, a left tributary to the Merrimack River, is the closest to the basin of the Suncook. The Soucook joins the Merrimack 4.8 km upstream of Suncook Village. The Soucook is geographically close to the Suncook River, so its smaller drainage area probably receives similar precipitation from each weather event. The closest tributary with the most similar drainage area is the Piscataquog River. It flows into the Merrimack River from the west 30 km downstream of the Suncook-Merrimack confluence (CDM, 2003). Both of these rivers have active USGS discharge gages that were put in place before the Suncook River gage was removed. All discharge data were obtained from the USGS Water Resources website (http://water.usgs.gov).

In order to determine which river serves as a better proxy for reconstructing the hydrograph for the Suncook River, we compared the discharge records of the three rivers in several different ways. We first compared the mean daily discharges for each of the three rivers to look at seasonal patterns of discharge. We then analyzed the daily discharge records for the shared period of the three rivers in order to find the river with

Figure 8: Location of the Suncook, Soucook, and Piscataquog USGS discharge gages showing gage status, active dates, and drainage area above the gage. Piscataquog River gage data is publicly available until 1978. It is currently run jointly by the USGS and U.S. Army Corps of Engineers, New England Division.

the most similar daily pattern of discharge. We then scaled the discharges of the Soucook and Piscataquog Rivers to the drainage area of the Suncook River to estimate discharges for the Suncook, and finally performed a statistical analysis to select the best proxy. The following sections present a detail description of each of them.

3.1.1. Comparing Mean Daily Discharges

We obtained the mean daily discharges for the Suncook, Soucook, and Piscataquog rivers from the USGS Water Resources website and plotted them together (Figure 9). Mean daily discharges are obtained by averaging, for every day, the discharges measured on that day on every year on record. The resulting graph shows that all three rivers follow the same general trend throughout the year. The discharge peaks in April, when the river carries snowmelt. At this point, the difference in discharges between the three rivers is greatest because the volume of water that a river carries is affected most closely by its catchment area. The discharge is lowest in September, when there is almost no difference among the three rivers. In general, the Piscataquog River discharge is the highest of the three because this river has the largest drainage area. The Soucook River has generally the lowest discharge because it also has the smallest drainage area.

The mean daily discharges that most closely resemble the record for the Suncook River is that of the Piscataquog River. Because mean daily discharges average out geographical variability in precipitation patterns, even when two rivers are far apart the drainage area is the determinant factor for the pattern of discharge.

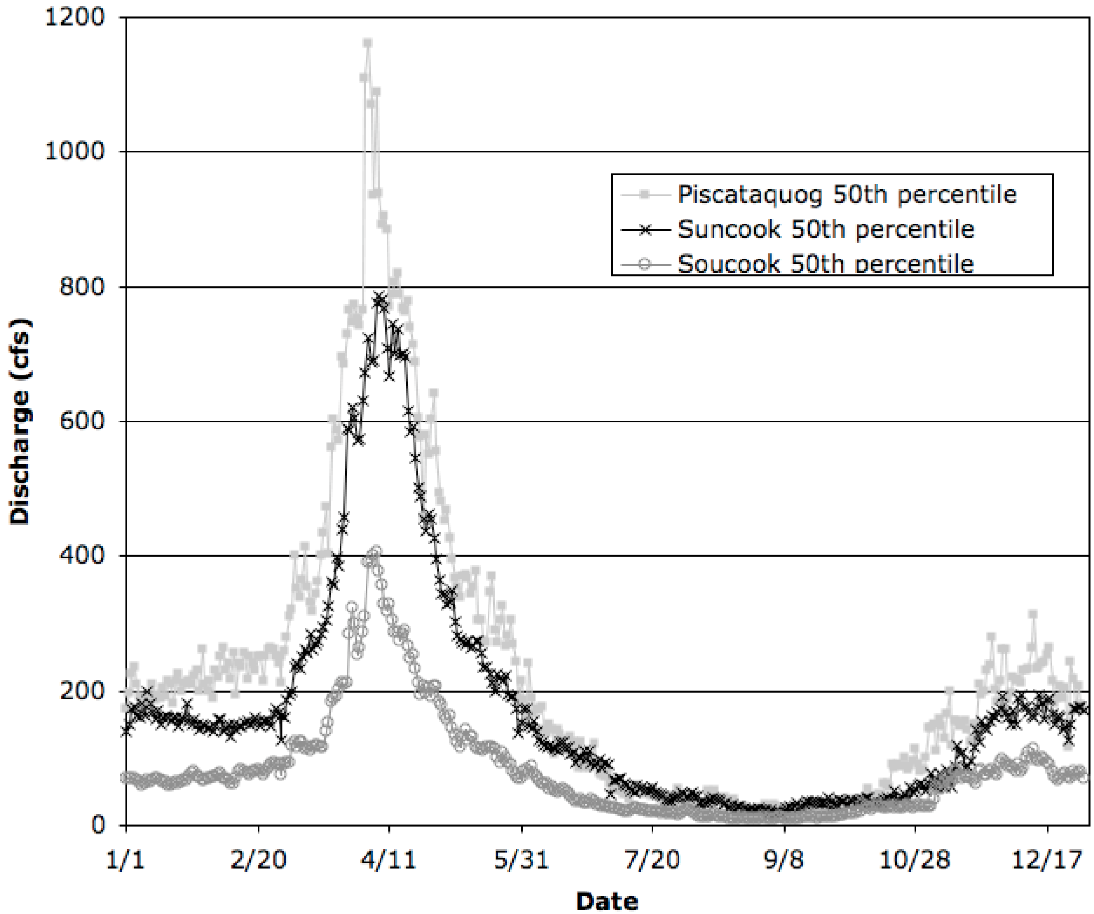

Figure 9: Daily discharges averaged for the length of each record for the Suncook, Soucook, and Piscataquog rivers, NH

3.1.2. Comparing Daily Discharges for the Shared Recording Period

The Suncook, Soucook, and Piscataquog rivers had active USGS discharge gages simultaneously between October 1, 1951 and September 30, 1970. A detailed look at the individual peaks of the three hydrographs shows that, while the amplitude that most closely resembles the hydrograph of the Suncook River is that of the Piscataquog River, the shape of the hydrograph is most similar to that of the Soucook River (Figure 10). This pattern is a direct result of the geographic location of the three rivers because, whereas the Suncook and Piscataquog rivers might be carrying similar volumes of water over the course of a year, the short-term pattern of that discharge depends directly on local meteorological conditions. We need to scale the discharges of both rivers to the drainage area of the Suncook River in order to select the best proxy.

3.1.3. Normalizing Daily Discharges for the Shared Recording Period

In order to directly compare the discharges of the three rivers and find the best proxy for the Suncook, we normalized the daily discharge measurements to the drainage area above the gage of the Suncook River using the equation

$$Q_{x_i}^{*} = \frac{Q_{x_i} \bullet A_{Suncook}}{A_x} \qquad (1)$$

where $Q_{x_i}^{*}$ is the normalized discharge for day *i* for either the Soucook or Piscataquog River, Q_{x_i} is the measured discharge for day *i* for that same river, $A_{Suncook}$ is the drainage area above the USGS gage on the Suncook River, and A_x is the drainage area above the USGS gage on either the Soucook or Piscataquog River. Figure 11 shows examples of the daily discharge measurements for the Suncook River, and the normalized discharges for the Soucook and Piscataquog rivers between 1951 and 1970.

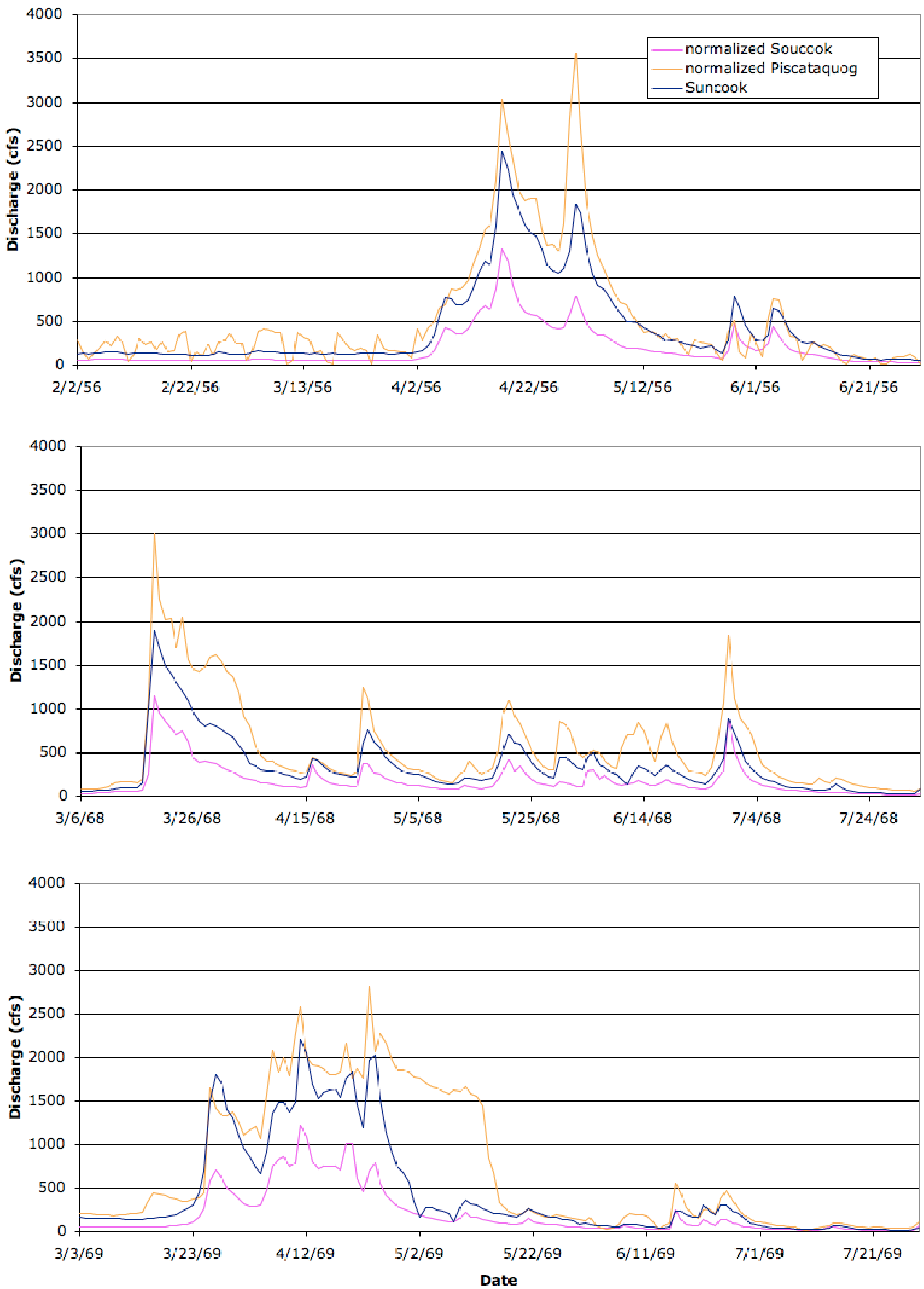

Figure 10: Examples of flooding events in the Suncook, Soucook, and Piscataquog Rivers hydrographs. The amplitude of the Piscataquog River discharge most closely resembles that of the Suncook River, but the pattern of the Soucook River is most similar to that of the Suncook River.

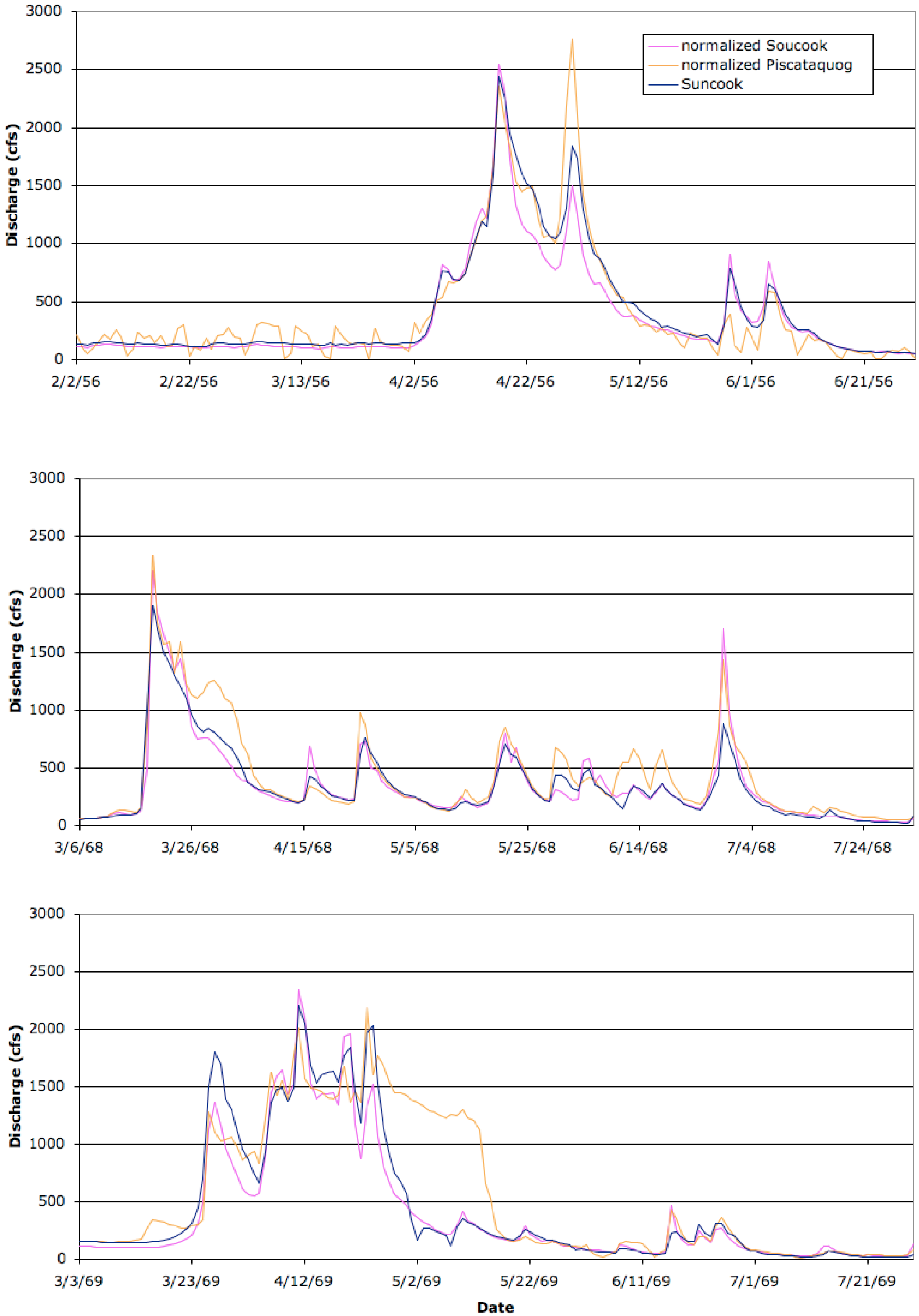

Figure 11: Examples of flooding events in the Suncook River and normalized Soucook and Piscataquog Rivers hydrographs. The normalized Soucook River hydrograph most closely resembles that of the Suncook River.

Figure 12 compares the Suncook River discharges with these normalized discharges for the Soucook and Piscataquog Rivers. The greater scatter of the normalized Piscataquog vs. Suncook River plot shows that there is a greater difference in the estimated and measured discharges than for the Soucook River.

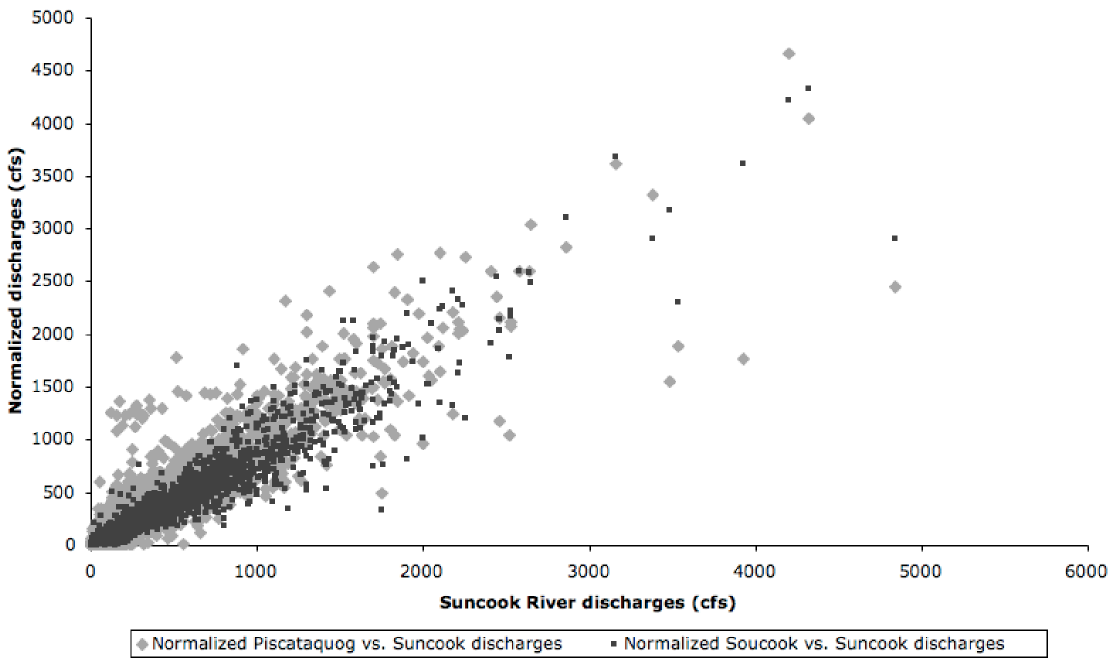

Figure 12: Scatter plot of the normalized discharges of the Soucook and Piscataquog River against the measured discharges of the Suncook River between 1951 and 1970. The normalized Soucook-Suncook comparison shows less scatter, suggesting that the Soucook River is a better proxy for the discharge of the Suncook River.

To quantify the statistical similarity between these three discharge records, we used the Pearson product-moment correlation coefficient $\rho_{x,Suncook}$ between the normalized Piscataquog, normalized Soucook, and the Suncook River discharges using the formula

$$\rho_{x,Suncook} = \frac{\text{cov}(x, Suncook)}{\sigma_x \bullet \sigma_{Suncook}} \tag{2}$$

where x is the normalized discharge for the Soucook or Piscataquog rivers, and the covariance $\text{cov}(x, Suncook)$ and standard deviation σ_i are given by

$$\text{cov}(x, Suncook) = E(x \cdot Suncook) - E(x)E(Suncook) \tag{3}$$

$$\sigma_i = \sqrt{E(i^2) - E^2(i)} \tag{4}$$

where $E(i)$ is the expectation, and i is the normalized discharge given by x or the discharge of the Suncook River. The correlation coefficient between the Suncook River discharges and the normalized discharge of the Soucook River was calculated to be 0.96, and between the Suncook River and the normalized Piscataquog River of 0.92. The highest correlation coefficient between the normalized Soucook River and the Suncook River discharges shows that this is the best proxy.

3.2. Reconstructing a Continuous Hydrograph for the Suncook River

In order to obtain the longest possible record for flooding in the Suncook River, we combined the existing discharge data for the Suncook River, recorded between 1918 and 1970, with the estimated discharges obtained from the normalized Soucook River record from 1970 to 2007.

3.3. Estimated Discharge in the Suncook River During the May 2006 Flood

The USGS determined that several tributaries to the Merrimack River in southern New Hampshire reached 100-year flood discharges during the May 2006 floods, as determined by measurements in their flood gages (Figure 13) (USGS, 2006). The Suncook River does not have an active gage, and thus is not included in this Figure. However, most of the tributaries to the Merrimack River around the location of the Suncook reached 100-year interval flood levels.

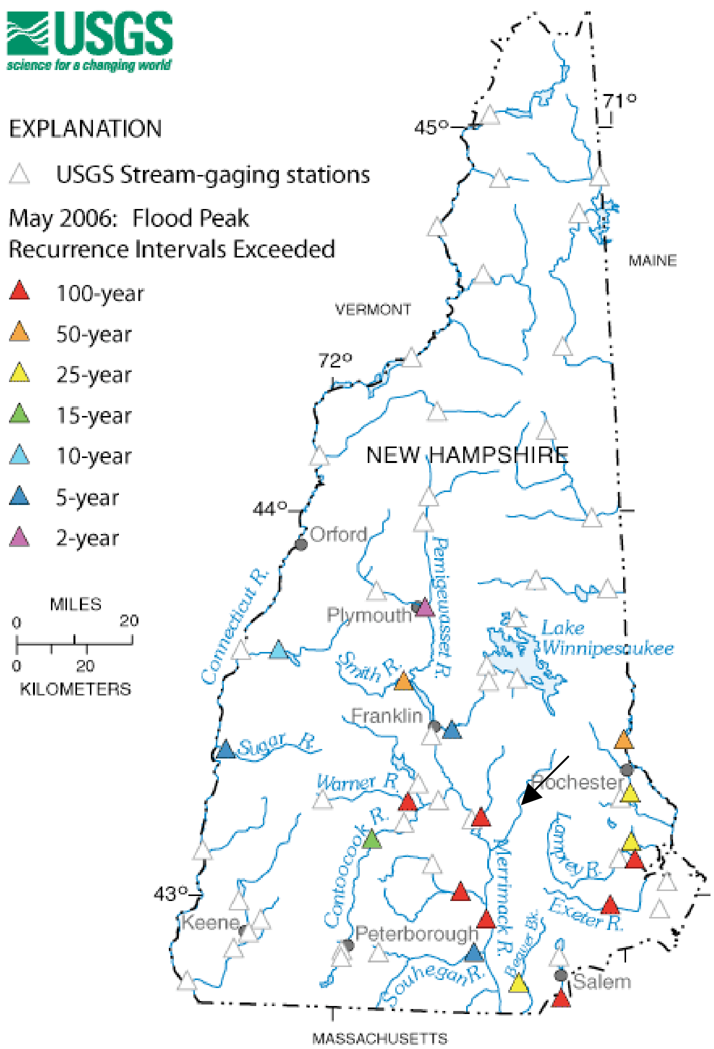

Figure 13: Flood recurrence intervals exceeded at USGS gages in New Hampshire. Black arrow marks location of avulsion site (Modified from USGS).

The peak discharge was reached in the Soucook River at 8:45 pm that day, with a discharge of 5110 cfs (provisional data) (Scott Olsen, USGS, personal communication). The time of peak discharge of different rivers during a flood depends strongly on the geometry of the basins and their geographic location. While we cannot assume that both rivers reached their peak discharges at the same time, accounts by local residents suggest that the level of the river was highest between the evening and midnight of May 14. By noon on May 15, the Suncook River had changed course. The calculated normalized peak discharge for the Suncook River is 9786 cfs.

Chapter 4

Flood Frequency Analysis for the Suncook River

In order to understand the magnitude of a flooding event in the context of the hydrologic history of a river, we must determine the recurrence interval for floods in that drainage area. The recurrence interval or return period for a flood of a certain discharge is the number of years that statistically pass between two events of equal or greater discharge. Recurrence intervals are obtained from a flood frequency analysis of the record of annual peak discharges for a river. An exceedance probability, or the probability that a flood of equal or greater magnitude will happen on the same year of a given event, is also calculated. For example, a 100-year flood has an exceedance probability of 0.01, or 1%. This means that, on the year a 100-year flood occurs, there is a 1% change that there will be a flood of equal or greater magnitude.

4.1. Methods

There are several methods to determine the flood frequency distribution for a given river that depend on the statistical methods used. The Interagency Water Advisory Committee on Water Data (1982) recommends the use of the Log-Pearson Type III distribution for the calculation of recurrence intervals. This method was first developed by Foster (1924). The Log-Pearson Type III distribution allows the calculation of discharges for events with return periods much larger than the available record. We will use this method to develop a flood frequency analysis for the Suncook River because it is the preferred technique by federal agencies in the United States.

Peak discharge data were obtained for the Suncook River from the USGS flood gage near Chichester, NH, for the period between 1918 and 1970. The peak discharges between 1971 to 2006 were estimated by normalizing the peak discharge measurements for the USGS gage on the Soucook River at Pembroke Road, near Concord, NH.

A table was constructed with the date and discharge of all annual peak discharge events Q (measured and estimated) for the Suncook River between 1918 and 2006. This table was then sorted by decreasing discharge. A rank m was assigned to each discharge, with 1 being the largest event recorded and n, the number of peak discharges on record, the smallest. We then calculated the logarithm of each of those discharges and determined the average of the discharges and the average of the logarithms of the discharges. We used these values to calculate the variance σ^2 and skewness coefficient C_s using the following formulas

$$\sigma^2 = \frac{\sum_i^n (\log Q_i - average(\log Q))^2}{n-1} \tag{5}$$

$$C_s = n \bullet \sum_i^n (\log Q_i - average(\log Q))^3 \tag{6}$$

To determine the recurrence interval, we used a table of frequency factors for log-Pearson Type III distributions (Haan, 1977, table 7.7). In this table, we used the skewness coefficient calculated above to obtain frequency factors K for recurrence intervals of 1, 2, 5, 10, 25, 50, 100, and 200 years. We then calculated the discharges associated with each recurrence interval using the equation

$$\log Q \bullet T_r = average(\log Q) + K \bullet \sigma \bullet \log Q \qquad (7)$$

where T_r is the recurrence interval. We also calculated the exceedance probability P, or the probability that another event of equal or larger magnitude occurs in any one year, using the equation

$$P = \frac{1}{T_r} \qquad (8)$$

The peak discharges used in the calculation of the discharges associated with each recurrence interval are available in Appendix A.

4.2. Results and Analysis

The discharges associated with each recurrence interval, as well as their exceedance probability, are summarized in Table 2 and Figure 14. Based on these values, the May 2006 flood exceeded the 100-year flood discharge but was smaller than the 200-year flood discharge.

The reconstructed flood history for the Suncook River shows that a flood in 1936 exceeded the discharge of the May 2006 flood. The 1936 flood had a peak discharge of 12900 cfs in the Suncook River, with a recurrence interval of more than 200 years.

Table 2: Discharge and exceedance probabilities expected for floods of increasing recurrence interval.

Recurrence Interval (years)	Discharge (cfs)	Exceedance Probability
1	873.046	100%
2	2350.332	50%
5	3667.540	20%
10	4722.192	10%
25	6273.308	4%
50	7602.798	2%
100	9089.387	1%
200	10757.560	0.5%

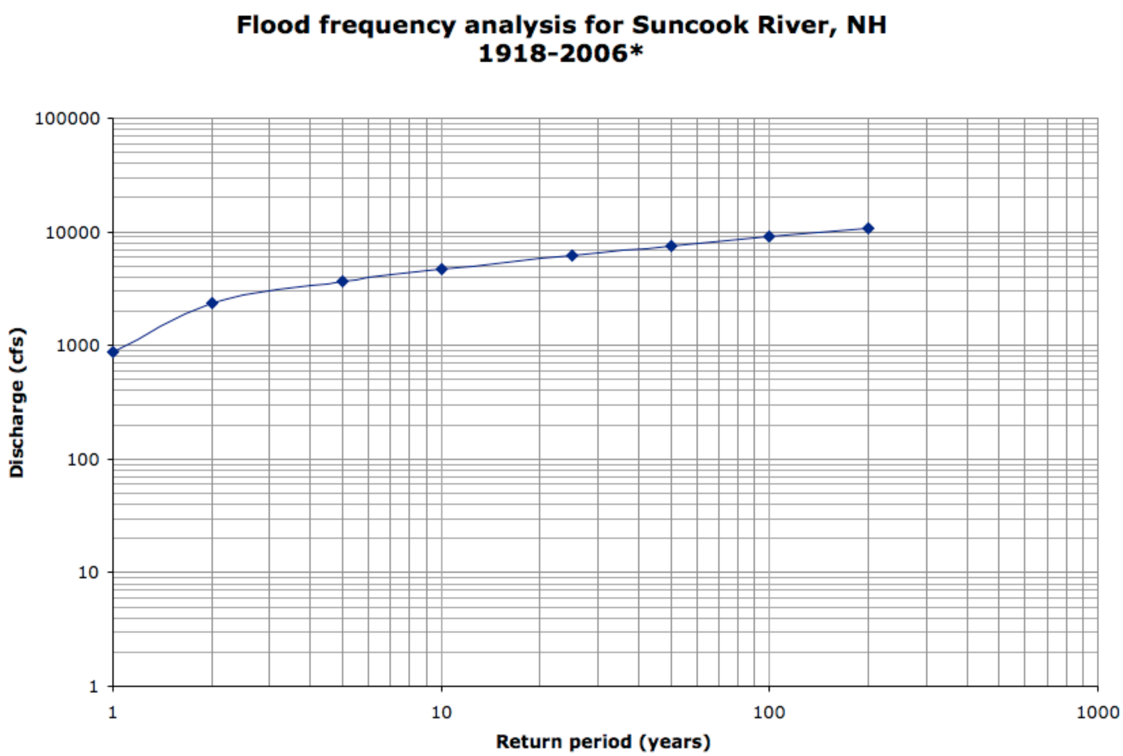

Figure 13: Flood frequency analysis for the Suncook River, NH, with data between 1918 and 2006.

Chapter 5

Drivers for the May 2006 Suncook River Avulsion

Slingerland and Smith's (2004) model for the occurrence of avulsions provides a method to study abrupt changes in channel position in environments where there is no net aggradation, making it ideal for the study of the Suncook River. By using their model, we can start to understand the controls of topography on the occurrence of avulsions. Slingerland and Smith's (2004) model assumed a system with suspended sediment of 0.4 mm in diameter. While the Suncook River has a broader distribution of sediment sizes, the average sediment size in overbank deposits is approximately 0.5 mm and thus close to the assumptions for the model. Slingerland and Smith's (2004) principal figure shows threshold ratios of water surface slopes for the formation of avulsions that heal (refills the breach with sediment), partial avulsion (does not continuously flow), and full avulsions (abandons the parent channel) (Figure 15). The vertical axis corresponds to a ratio of height of the breach on the levee of the channel to water depth on the parent channel.

It is not possible to recreate the details of the pre-avulsion topography between the avulsion site and the secondary channel because there is a poor record of the activity in Cutter's Pit. Because the relief of the back wall of the quarry with respect to the parent channel cannot be measured, we can only plot the conditions of the Suncook River on Slingerland and Smith's (2004) plot with respect to the horizontal axis.

We could not directly measure the water surface slopes for the new and parent channels because water was not flowing in the parent channel during our field season.

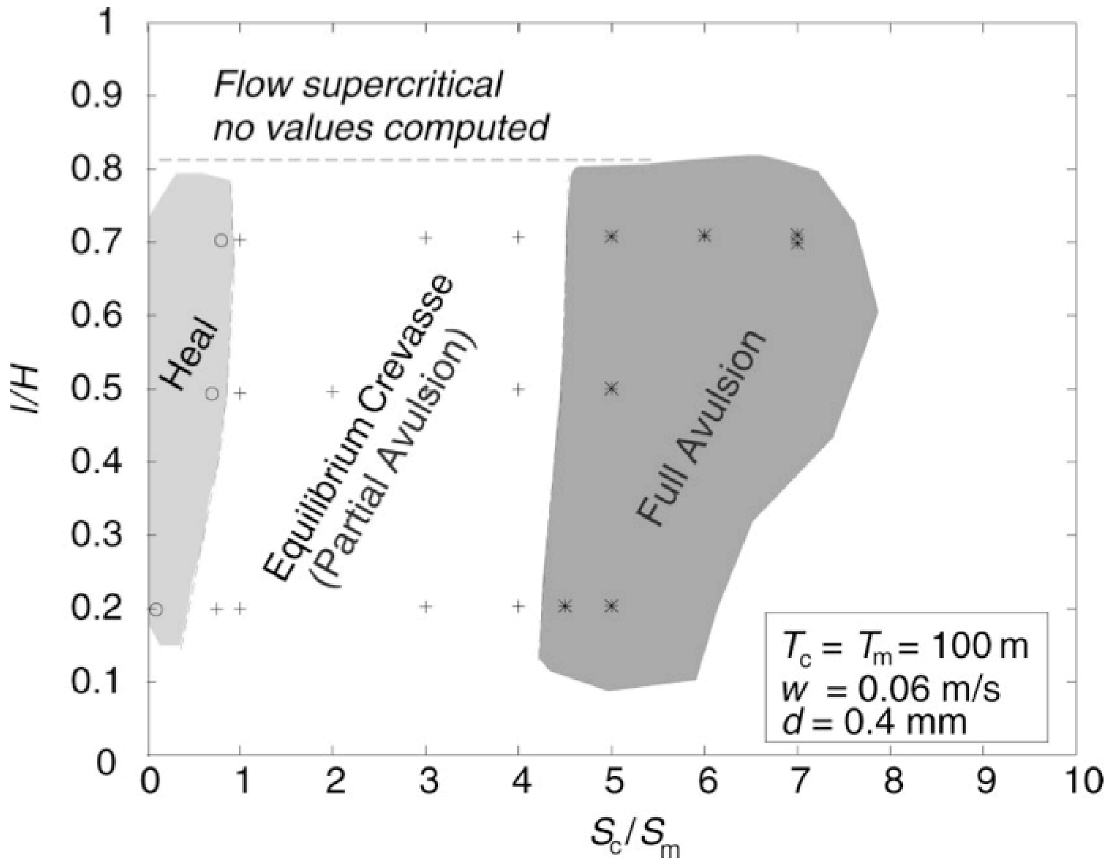

Figure 15: Predicted result of the creation of a bifurcation in a river, assuming a median grain size for suspended sediment of 0.4 mm. Horizontal axis corresponds to the ratio of the water surface slope of the new channel and the parent channel. Vertical axis is the height of the lip that the water has to flow over relative to the depth of the parent channel (From Slingerland and Smith, 2004)

However, it is possible to assume that the water surface slope of a river is approximately equal to its bed surface slope in steady uniform flow. We calculated the distances along the channel and the relief between the avulsion site and the respective base levels for the parent and new channels to obtain the bed slopes. For the parent channel, we used the area behind Huckins Mill Dam as the base level. For the new channel, the base level was assumed to be the site where the newly carved channel joins the secondary pre-avulsion channel.

We used the USGS Suncook, NH quadrangle, 1:24000 topographic map (1982) and ArcGIS 9 to measure the bed surface elevations for the end points of the two channels, as well as the horizontal distances the water traveled between those points (Figure 16). The bed surface slope is defined by the equation

$$S = \frac{H}{l} \tag{9}$$

where S is the bed slope of the channel, H is the relief between the avulsion site and the base level in meters, and l is the distance along the channel between those two points in meters. The ratio of the bed surface slope of the new channel path to the bed surface slope of the main channel is 2.81 The Slingerland and Smith (2004) model suggests that this ratio would create a partial avulsion (Figure 17).

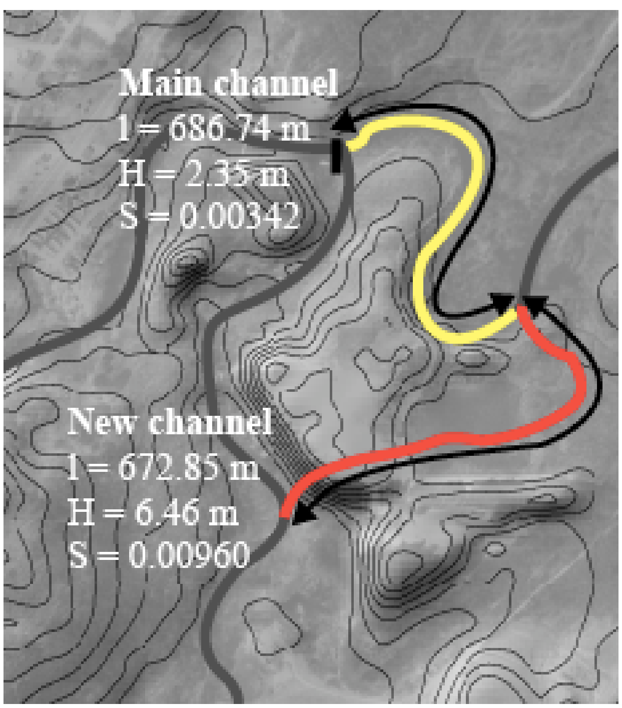

Figure 16: Channels and measurements used in Slingerland and Smith's model. Yellow channel is the parent channel, while red channel corresponds to the newly carved path (Modified from USGS Suncook, NH quadrangle, 1:24000 topographic map, 1982).

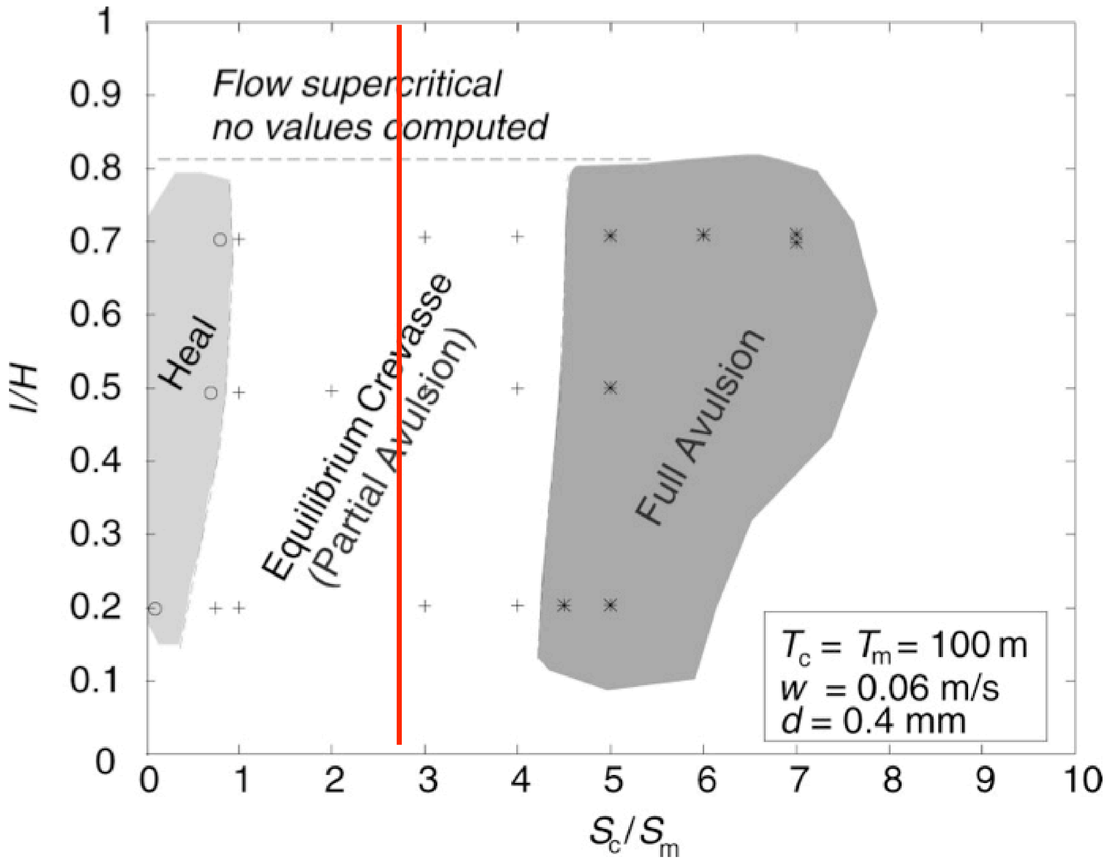

Figure 15: Predicted result of the creation of a bifurcation in a river, assuming a median grain size for suspended sediment of 0.4 mm. Horizontal axis corresponds to the ratio of the water surface slope of the new channel and the parent channel. Vertical axis is the height of the lip that the water has to flow over relative to the depth of the parent channel (From Slingerland and Smith, 2004)

For the new channel path, the bed slope is a good approximation to the water surface slope. In the pre-avulsion main channel, however, this is not the case. The backwater behind Huckins Mill Dam reached past the site of avulsion, and reduced the water surface slope of the channel to approximately zero, and the water surface slope ratio infinitely large. By increasing the ratio and allowing the Suncook River system to reach the full avulsion field in Slingerland and Smith's (2004) model, Huckins Mill Dam could have been a direct driver of the May 2006 avulsion.

Chapter 6

Geologic Conditions Affecting the May 2006 Suncook River Avulsion

Several hypotheses for the occurrence of avulsions suggest that decreases in the capacity of the parent channel to transport water and sediment discharges due to changes in geometry or blockages of the path allow for water to pile overbank and drive avulsions (Schumm et al., 1996; Jones and Harper, 1998; Field, 2001, and others). Schumm et al. (1996), for example, suggest that, in the Ovens and King Rivers of Victoria, Australia, the increasing sinuosity of anastomosing channels as they age reduces their hydraulic efficiency and drives avulsions.

In this chapter, we propose that armoring in the abandoned channel and soft sands in the new channel and the banks at the avulsion site positively influenced the occurrence of an avulsion. We also give an overview of the incisional mechanisms that governed the incision of the new Suncook River channel and argue that migration rate of the knickpoint during incision is critical for the occurrence of a full avulsion.

6.1. Prevention of Incision in the Parent Channel by Armoring

Sediment is picked up from the bottom of the channel when the shear stress of the water acting on the bed is greater than a critical shear stress that is needed to move the grains. The basal shear stress exerted by the water depends on water depth and slope, while the critical shear stress depends only on the submerged density of the grains and their diameter. During floods, water depth increases, also increasing the shear stress applied on the channel bed and mobilizing grain sizes larger than are mobile during normal flow conditions.

We propose that the boulders that are exposed in the main channel of the Suncook protected the bed against incision through armoring. Armoring occurs when the fine sediment on the top of the bed of a river is removed during periods of low shear stress flow while the largest fractions of sediment are not moved. The coarse material left behind on the surface of the channel bed protects the fine material underneath from mobilization (Reed et al., 1999). The thick black patina that covers these boulders shows that they have not been moved by recent floods (Figure 18).

We propose that armoring prevented the channel from deepening in response to the flood. This kept the slope of the channel from steepening to allow more sediment to

Figure 18: Boulder reach in principal channel of the Suncook, looking downstream.

be transported, maintaining the hydraulic capacity of the channel low. Schumm et al. (1996) suggest that reductions in hydraulic efficiency reduce the bankfull discharge for a river and thus increase the frequency of overbank flooding. In this case, the lack of incision allowed a high proportion of the water to flow overbank and find a favorable path that became the avulsion.

6.2. Role of Substrate Strength in the Migration of Knickpoints

Overbank flow cannot erode efficiently unless it concentrates along a topographic low. If the overbank flow converges in a valley or along a pre-existing channel, the shear stress of the water on the bed increases and the flow has the power to incise (Field, 2001). Water flowing over the downstream ridge of Cutter's Pit had a high capacity for erosion because most suspended sediment had settled in the stagnant water of the quarry. As it went over the gap on the back wall, water converged and quickly removed material from the wall. As water went over the step and onto the downstream floodplain a knickpoint started migrating upstream, carving the new channel into the topography.

For an avulsion to reach completion, the head of the new channel has to retreat back so it breaches the wall of the parent channel and captures the flow of the river. For a full avulsion to occur in a single flood event, as it did in the Suncook River, this has to occur before the flood levels recede; otherwise no water will flow over the knickpoint and cause it to migrate upstream. The strength of the substrate determines the rate at which knickpoints migrate through it. In bedrock, for example, the rate is on the order of millimeters per thousand years (Gardner, 1983), while in weakly cohesive sediments such as clays knickpoint migration rates are closer to meters per year (Thomas et al., 2001).

We suggest that it is necessary for the substrate in the path of the new channel to be easily erodible in order for the knickpoint to migrate upstream and connect to the main channel before the flood subsides. The glacial sands and clays in the Suncook area were easily carried away by the flood and allowed the rapid migration of the knickpoint. If the material through which the knickpoint migrated had been highly cohesive, the rate of headwall erosion would not have been high enough to connect the new and parent channels in time.

We propose that it was also necessary for the path of the new channel to be free of obstacles such as boulders or bedrock reaches that would have prevented the knickpoint from migrating. If the obstacle had been near the surface, at an elevation similar to that of the avulsion site, the knickpoint would have reached the avulsion site. Instead, any shallow channel formed upstream of the knickpoint would have gradually filled up with sediments during small floods, and the avulsion would have healed. If the obstacles in the path of the new channel were deep under the surface, part of the knickpoint could have continued to travel upstream and reach the main channel. An avulsion would have occurred, but the new channel would have had a step in the longitudinal profile (Figure 19).

To test this hypothesis, we studied the longitudinal profiles of the abandoned and active channels of the Suncook River. During November and December of 2006 we conducted field surveys of the abandoned and new channels of the Suncook River. We used a setup of a commercially available laser rangefinder with built-in inclinometer and digital compass (Impulse/Mapstar by Laser Tech), connected to a PDA (TDS Recon

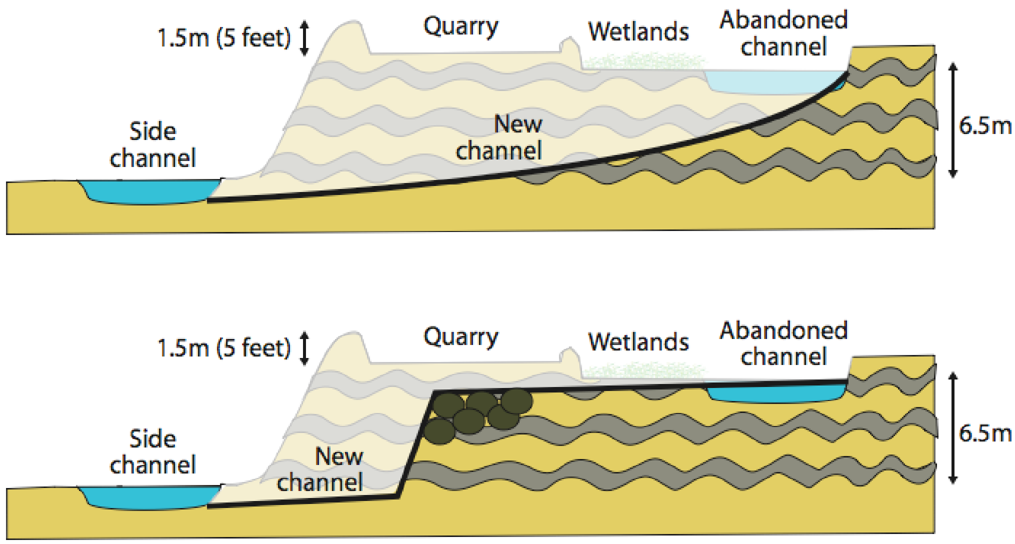

Figure 19: Schematic diagrams of the final profile of the new channel of the Suncook River without obstacles in the substrate (top), and with boulders (bottom). We suggest that obstacles such as boulders or bedrock in the path of the knickpoint would have left a step in the longitudinal profile of the new channel, and possibly prevented an avulsion.

400), and a Socket Bluetooth GPS. Every data point is automatically recorded and displayed on the PDA by custom Arcpad software developed at MIT.

The abandoned channel was surveyed downstream from the avulsion site along the middle of the channel bed. The survey was terminated when ponded water (and during winter, ice) made it impossible to continue along the bed. We were unable to survey along the channel bed in the new channel because of the depth of the water and the high flow velocities. This channel was surveyed following the water surface along the right bank, starting 50 m upstream of the junction with the secondary channel and proceeding upstream. The density of data points increased to approximately one every 10 m near the avulsion site. Access was difficult starting 50 m upstream of the site of avulsion and continuing upstream. The survey was terminated where the banks dropped vertically into the water and it was impossible to reach the water surface. The results from our field surveys are shown in Figure 20.

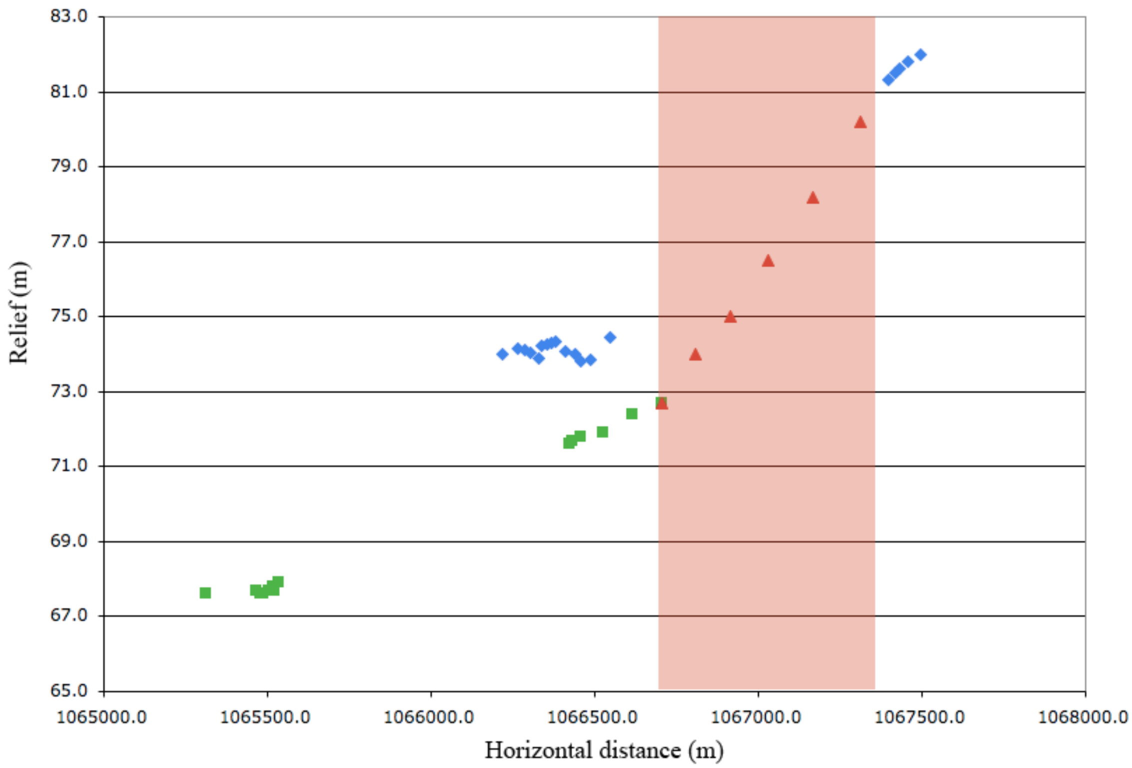

Figure 20: Field survey measurements showing partial long profiles for the Suncook River. The profile of the new channel (green) is lower than the profile of the parent channel (blue). Area in red shows the step in the longitudinal profile that corresponds to the captured knickpoint.

Our surveys show that the profile of the new channel is lower than that of the parent channel. This difference in elevation allows the new channel to route all of the flow that comes down the Suncook River. A reach upstream of the avulsion site has a much higher slope than the channel upstream, or either of the channels downstream. We hypothesize that this section corresponds to a portion of the knickpoint that was captured by a reach of boulders are seen exposed in the channel. Eyewitnesses report that these boulders, as well as other boulder reaches observed upstream, were not exposed on the channel bed before the avulsion. We propose that only a portion of the knickpoint continued migrating upstream and incising into the bed. While we are not able to confirm this hypothesis from the channel profile surveys, we hypothesize that the profile upstream of this reach is lower than the continuation of the abandoned channel profile. The presence of the steep bouldery reach confirms our idea that the avulsion channel could have not formed if there were immovable obstacles in the path of the knickpoint.

6.3. Estimates of Knickpoint Migration Rate

Local residents observed the knickpoint that carved the new channel of the Suncook River migrating during the flood. However, there are no direct measurements of its migration rate. In order to understand the importance for the erodibility in the substrate for an avulsion to come to completion, we estimated the migration rate of the knickpoint during the May 2006 Suncook River avulsion.

While there are no known witnesses to the start of the migration of the knickpoint and thus no reported initial time, we know that incision could only have started once the water pooled over 1.5 m high in the sand pit. This is the depth that allowed the water to flow over the back wall and onto the downstream floodplain. We assume that water could have reached this level only when the flood discharges reached a maximum. The USGS recorded that the peak discharge for the Soucook River occurred at 8:45 pm of May 14 (preliminary data) (Scott Olsen, USGS, personal communication). While we cannot assume that the peak discharge was also reached in the Suncook River at that time because of the differences in the geometry and location of the catchments for the two rivers, accounts by local residents (Orff, 2006) suggest that the peak discharge was reached sometime in the evening of May 14. The time the knickpoint reached the avulsion site, considered the effective end time for the migration of the knickpoint, is known from anecdotal evidence to be noon on May 15 (Orff, 2006). At this time water was seen flowing upstream at the site of Huckins Mill Dam as it drained into the new channel. We calculated the knickpoint migration rate for 12 hours and 24 hours of migration to obtain endmembers. The distance traveled by the knickpoint was calculated along the length of the new channel from the point where it joins the side channel of the Suncook to the avulsion site, and measured approximately 600 m.

To calculate the knickpoint migration rate, we used a simple equation for velocity

$$V = \frac{l}{t} \tag{10}$$

where V is the knickpoint migration rate and t is the time it took to migrate from the starting point to the avulsion site. For 12 hours, the knickpoint migration rate was estimated as 50 m/hr or 1.2 cm/s and for 24 hours as 25 m/hr or 0.6 cm/s.

The knickpoint migration rate allows us to calculate the volumetric rate of removal of material during the avulsion. For the calculation, we assume that the channel is of uniform width and depth and that no erosion occurred anywhere else on the floodplain, even when this is not supported from field observations. The channel is assumed to be on average 30 m wide, while the depth will be assumed to be uniformly 5 m. In reality, the depth increases downstream. We can then calculate the volume of material that was mobilized per hour during the avulsion using the equation

$$R = b \bullet h \bullet V \tag{11}$$

where R is the rate of removal of material, b is the width of the channel, and h is the channel depth. The resulting rate of removal of material is 7500 m^3 hr^{-1} for 12 hours of migration and 3750 m^3 hr^{-1} for 24 hours. Using our estimate of duration of the migration of the knickpoint, we calculate the total volume of material removed as approximately 90,000 m^3. Estimates by the New Hampshire Geological Survey (Wittkop et al., 2007) of the volume of material removed during the avulsion are closer to 115,000 m^3. Their value was calculated through field surveys conducted in the days following the avulsion, taking into account the variability in channel depth and width, as well as the erosion that occurred overbank. We consider the calculations by the New Hampshire Geological Survey to be more accurate than ours, but we are pleased to see that our estimates of knickpoint migration rates allow us to obtain a similar value.

Chapter 7

Discussion

Avulsions have been studied in environments where river channels are actively aggrading. The Suncook River, where several small dams reduce the sediment supply and thus prevent aggradation, provides a challenge for the understanding of avulsions. The most widely accepted theories for the occurrence of these abrupt changes in channel position focus on the superelevation of the channel bed above the surrounding floodplain. This process can occur only in a net-depositional environment. We chose to study the Suncook River avulsion using Slingerland and Smith's (2004) model because it is the only proposed hypothesis that can be directly applied to an environment where there is no net aggradation.

Slingerland and Smith's (2004) hypothesis presented the challenge of calculating the water surface slope for the pre-avulsion Suncook River after the geometry of the channel had been modified by the avulsion. Conditions of steady, uniform flow could have been assumed for the parent channel if Huckins Mill Dam and the smaller, secondary dam had not been present. Under these conditions, the water-surface slope is approximately equal to the bed-surface slope. In Slingerland and Smith's (2004) model, the low ratio of the water surface slopes of the new channel to the parent channel would suggest that only a partial avulsion could occur.

Huckins Mill Dam ponded water past the avulsion site, reducing the water-surface slope to almost zero, and thus infinitely increasing the water surface slope ratio. This high ratio of water-surface slopes would have created a full avulsion in Slingerland and

Smith's (2004) model. The presence of Huckins Mill Dam, however, might have not only affected the type of avulsion that occurred but also the initial formation of the new channel. The impounding of water behind Huckins Mill Dam increased the depth of overbank flooding at the site of avulsion, thus increasing the volume of water flowing into Cutter's Pit and the depth of ponded water in this quarry. Only when the depth of standing water reached the height of lowest point of the back wall of Cutter's Pit did the new channel form.

The role of Cutter's Pit on the formation of the avulsion has been widely debated (Connaboy, 2006a). The New Hampshire Geological Survey officials have publicly stated that while the presence of the quarry could have accelerated the process, an avulsion would have naturally occurred at this site (Connaboy, 2006a). Before material started being removed from the site of the quarry in the 1960s, a large hill made up of glacial material stood in its place (Connaboy, 2006b). Wittkop et al. (2007) calculated that the depth of the floodwaters at the site of avulsion had to be 1.5 m higher than during the May 2006 flood in order to flow over the natural topography. Without Cutter's Pit, the discharge of the May 2006 flood probably would not have breached the topographic high.

The presence of Cutter's Pit was not enough to cause an avulsion, however. The creation of a gap on the back wall of the quarry by the frequent transit of vehicles from the pit to the road downstream was vital for the occurrence of an avulsion. If the height of the back wall had been uniformly high, water could not have flowed over it and onto the downstream floodplain and thus an avulsion would not have occurred. The increasing weight of the deepening water as the flood progressed, however, could have caused the back wall to fail through the same processes that break earthen dams and levees. These levees and dams often fail when the pressure of the water at the base of the wall drives seepage erosion and creates a slit that grows increasingly larger until the structure breaks (e.g., Ojha et al., 2001; Ojha et al., 2003).

The May 2006 flood is not the largest flood on record for the Suncook River. Our reconstructed hydrograph and flood frequency analysis for show that the 1936 peak discharge was greater than the May 2006 flood, corresponding to a 200-year recurrence interval. There are few records of the damage caused by the 1936 floods. Heavy rains and the rapid meltdown of snow and ice created heavy floods. The ice covering the swelling Suncook River broke on March 19, 1936 (Manchester Leader and Evening Union, 1936), sending ice rafts downstream and threatening bridges and dams (Yeaton, 1995). Even with the higher discharge, however, this flood did not cause an avulsion.

The absence of Cutter's Pit required water levels to be 1.5 m higher at the site of avulsion than during the 2006 flood for water to flow across the topographic high and onto the downstream floodplain (Wittkop et al., 2007). The greater discharge, along with the presence of Huckins Mill Dam, could have allowed the water to reach this depth. We know, however, that Huckins Mill Dam was reconstructed in 1937 (Orff, 2006). While there is no direct evidence that the dam was destroyed, it is possible that the ice floats or high discharges removed all or part of the dam. This would have reduced the backwater depth and thus prevented water from flowing onto the downstream floodplain and creating an avulsion.

Chapter 8

Conclusions

The mechanisms that govern avulsions in net-depositional landscapes are well understood. Avulsions in transient landscapes, however, provide a challenge to our current theories. Channels in these environments are responding to recent changes in topography, erosion, and deposition, and often do not show the aggradational patterns required by the existing theories. The main purpose of our research is to understand the drivers for avulsions in these transient landscapes, using as an example the May 2006 Suncook River avulsion, near Epsom, NH.

The Suncook River avulsed between May 14 and 15, 2006. Water flowed overbank over wetlands and ponded in a low-lying sand pit. Water overflowed the back wall of the quarry and onto the downstream floodplain. The new channel connects the main Suncook River from the avulsion site to a secondary channel, continuing on the pre-existing channel downstream. The parent channel presently carries no flow.

We chose the Suncook River avulsion as the field site for this study because it records a recent event. Evidence for the pre-avulsion characteristics of the channel are still present. In addition, the mechanisms that controlled the avulsion are still at play and continue to change the morphology of the channel. The close resemblance of the setting of the Suncook River to many other sites in New England provides a perfect setting for determining the risk of avulsions in this environment.

We reconstructed the hydrograph for the Suncook River by combining the available discharge data for this river with the record for the nearby Soucook River scaled to the drainage area of the Suncook River. With the complete reconstructed hydrograph we could understand the magnitude of the May 2006 flood in the context of the last 89 years of the hydrologic history of the river. This long record allowed us to more precisely develop a flood recurrence analysis for the Suncook River. The May 2006 flood was calculated to correspond to a 100-year recurrence interval, but was not the largest flood in record. Spring floods in 1936 exceeded this discharge with a 200-year recurrence interval.

We used existing avulsion theories to understand the mechanisms that governed the May 2006 event in the Suncook River. Models for superelevation (e.g. Brizga and Finlayson, 1990; Bryant et al., 1995; Heller and Paola, 1996; Mohrig et al., 2000) cannot be directly used to study this setting because there is no net deposition to raise the channel above its surrounding floodplain. The site of avulsion, however, is at a higher elevation than the floodplain onto which water flowed during the May 2006 flood, acting as superelevation. Slingerland and Smith (2004) provide a model that uses a high water surface slope between the avulsion channel and the parent channel as a predictor of the occurrence of avulsions. Their model suggests that the Suncook River could have formed a partial avulsion only if both the new and parent channel showed steady, uniform flow. The parent channel of the Suncook River, however, was dammed by Huckins Mill Dam, which impounded water upstream past the site of avulsion. Impounding during the May 2006 flood reduced the water-surface slope of the parent channel, increasing the ratio of water-surface slopes and allowing, under Slingerland and Smith’s model, a full avulsion to take place. The impounding was also necessary for the overbank water depth at the avulsion site to be high enough to flow over the topographic divide and reach the downstream floodplain.

Specific geologic characteristics of the avulsion site at the Suncook River also contributed to the occurrence of the avulsion. We suggest that regional patterns of easily erodible and resistant substrates governed the choice of path of the new channel. Armoring by boulders and shallow bedrock in the main channel protected the bed from incision to accommodate the increased discharge. Weak and easily movable glacial sands and clays along the new path allowed the rapid migration of the knickpoint that created the avulsion channel. The knickpoint migration was also aided by the absence of obstacles along this path. A reach of boulders or a bedrock ridge, both plausible in the context of the regional geology, would have created a step in the topography and prevented the formation of an avulsion. This hypothesis is supported by our field observations of a step in the profile of the channel at a reach of boulders upstream of the avulsion site.

The timing of the start of the migration of the knickpoint is poorly constrained. We can assume that retreat of the knickpoint started as peak discharge was reached, because only the highest water levels could have flowed over the topographic high. The time of connection of the new channel to the parent channel is, however, well constrained. The new channel formed during a period of 12 to 24 hours. We estimated the knickpoint migration rate necessary to create the new channel for these two durations, calculating values between 25 and 50 m/hr.

We propose that several conditions are necessary for an avulsion to occur in a transient landscape. A path with a slope steeper than the parent channel must exist with no topography over which water cannot flow during a high flood. A shallow slope in the main channel can be achieved through impounding behind a dam. The substrate of the new path and the bank of the parent channel must be weak and easy movable. No obstacles can exist in the path of the channel that would impede the migration of a knickpoint. Armoring in the parent channel also facilitates the occurrence of an avulsion because, by preventing incision, it allows water to go overbank and find a new path.

With only one site studied so far, there are still several questions that must be answered before we can develop a model for avulsions in transient landscapes. The most relevant is whether these conditions exist only in the Suncook River or if they are also present in other sites. Several major avulsions have been found throughout New England that can be used to continue to develop our model. It is also important to understand if the secondary channel of the Suncook River is the product of a partial avulsion. If it is, it could serve as a control experiment for anthropogenic drivers for avulsions, inasmuch as the lack of historical record suggests that it occurred before settlement of the area.

No avulsion occurred during the 1936 flood, even when the discharge was higher than during the 2006 floods. We propose that the area between the avulsion site and the downstream floodplain was blocked by natural topography. By 2006, this topography had been removed by activity at Cutter's Pit. It is also possible that Huckins Mill Dam collapsed during the flood, diminishing the backwater and increasing the slope of the parent channel.

The reduction of the water surface slope behind small mill dams like Huckins Mill Dam is a direct driver for avulsions. In 2004, there were 4407 dams in Massachusetts and 1483 dams in New Hampshire (Association of State Dam Safety

Officials, 2004), most of which are small. The presence of these dams could be drastically increasing the risk of avulsions at each of these sites. If these dams were removed, the risk of flooding around rivers would increase. The increased risk of avulsions from small mill dams should be included when considering the benefits and disadvantages of the removal of these dams.

There are currently models that are attempting to understand avulsions in net-depositional landscapes such as alluvial fans, deltas, and floodplains. Avulsions in transient environments such as New England, where there is no net aggradation, still constitute a challenge to our understanding of these processes. Our work is a first approach at developing a specific model for avulsions in these special settings.

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Appendix A: Peak discharges used in the calculation of the recurrence interval for floods in the Suncook River. White boxes represent values measured in the Suncook River, while gray boxes are peak discharges estimated from the measurements in the Soucook River. The data for 2006 is provisional.

All data, in chronological order

Date	Soucook discharge (cfs)	Suncook discharge (cfs)
3/29/19		1800
3/27/20		2350
6/22/22		2130
4/7/23		6580
4/7/24		3940
3/30/25		2780
4/26/26		1920
3/18/27		2620
3/16/29		2350
3/26/30		2020
3/29/31		1530
4/13/32		2430
4/19/33		3930
4/1/34		4160
1/10/35		2200
3/19/36		12900
2/23/37		4670
11/29/37		2460
4/20/39		2130
4/13/40		4090
2/9/41		1160
3/10/42		2200
12/2/42		1420
9/15/44		1470
3/22/45		1960
3/10/46		2100
4/7/47		1200
3/22/48		3900
1/6/49		1300
4/6/50		1430
4/4/51		2480
4/6/52		3300
3/27/53		5760
5/10/54		4720
11/4/54		1590
4/17/56		2610
1/24/57		950
4/7/58		1930
4/3/59		3480

All data, by descreasing discharge.

Date	Soucook discharge (cfs)	Suncook discharge (cfs)
3/19/36		12900
5/15/2006*	5110	9795.726496
3/14/77	3700	7092.796093
4/7/23		6580
3/27/53		5760
6/1/84	2880	5520.879121
4/1/87	2720	5214.163614
4/5/60		5200
3/14/77		4900
5/10/54		4720
2/23/37		4670
4/17/96	2320	4447.374847
4/1/34		4160
4/13/40		4090
4/7/24		3940
4/19/33		3930
1/27/86	2050	3929.79243
3/22/48		3900
6/17/98	2020	3872.283272
4/4/05	1930	3699.7558
3/8/79	1820	3488.888889
4/3/59		3480
4/2/76		3380
10/22/96	1750	3354.700855
4/6/52		3300
12/18/03	1550	2971.306471
2/11/70		2900
3/30/25		2780
2/27/81	1420	2722.100122
3/31/93	1400	2683.760684
3/18/27		2620
4/17/56		2610
4/1/62		2600
3/20/83	1330	2549.57265
4/4/51		2480
11/29/37		2460
4/13/32		2430
4/7/89	1260	2415.384615
4/23/69		2380

Date	Soucook discharge (cfs)	Suncook discharge (cfs)
4/5/60		5200
4/17/61		1360
4/1/62		2600
10/7/62		1840
4/15/64		2000
4/17/65		793
3/25/66		1100
4/3/67		1870
3/19/68		2000
4/23/69		2380
2/11/70		2900
4/14/71		1200
3/23/72		2000
4/4/73		1680
12/21/73		1780
3/21/75		2350
4/2/76		3380
3/14/77		4900
3/14/77	3700	7092.796093
1/10/78	1130	2166.178266
3/8/79	1820	3488.888889
4/11/80	1030	1974.481074
2/27/81	1420	2722.100122
10/24/81	1140	2185.347985
3/20/83	1330	2549.57265
6/1/84	2880	5520.879121
3/13/85	807	1546.996337
1/27/86	2050	3929.79243
4/1/87	2720	5214.163614
4/7/89	1260	2415.384615
8/25/90	902	1729.108669
10/25/90	1020	1955.311355
11/23/91	818	1568.083028
3/31/93	1400	2683.760684
4/5/94	669	1282.454212
3/9/95	1150	2204.517705
4/17/96	2320	4447.374847
10/22/96	1750	3354.700855
6/17/98	2020	3872.283272
9/17/99	886	1698.437118
3/29/00	1000	1916.971917
4/14/01	1210	2319.53602
5/14/02	667	1278.620269
3/27/03	1050	2012.820513
12/18/03	1550	2971.306471
4/4/05	1930	3699.7558
5/15/2006*	5110	9795.726496

Date	Soucook discharge (cfs)	Suncook discharge (cfs)
3/27/20		2350
3/16/29		2350
3/21/75		2350
4/14/01	1210	2319.53602
3/9/95	1150	2204.517705
1/10/35		2200
3/10/42		2200
10/24/81	1140	2185.347985
1/10/78	1130	2166.178266
6/22/22		2130
4/20/39		2130
3/10/46		2100
3/26/30		2020
3/27/03	1050	2012.820513
4/15/64		2000
3/19/68		2000
3/23/72		2000
4/11/80	1030	1974.481074
3/22/45		1960
10/25/90	1020	1955.311355
4/7/58		1930
4/26/26		1920
3/29/00	1000	1916.971917
4/3/67		1870
10/7/62		1840
3/29/19		1800
12/21/73		1780
8/25/90	902	1729.108669
9/17/99	886	1698.437118
4/4/73		1680
11/4/54		1590
11/23/91	818	1568.083028
3/13/85	807	1546.996337
3/29/31		1530
9/15/44		1470
4/6/50		1430
12/2/42		1420
4/17/61		1360
1/6/49		1300
4/5/94	669	1282.454212
5/14/02	667	1278.620269
4/7/47		1200
4/14/71		1200
2/9/41		1160
3/25/66		1100
1/24/57		950
4/17/65		793